Applied Physics Laboratory
College of Ocean and Fishery Sciences • University of Washington

1013 NE 40th Street
Box 355640
Seattle, WA 98105-6698

206-543-1300
FAX 206-543-6785
www.apl.washington.edu

7 May 2008
Serial 5C7047

To: Dr. Ellen S. Livingston
Office of Naval Research, Code 0321
875 N. Randolph St.
One Liberty Center
Arlington, VA 22203

From: Dajun Tang, Principal Investigator

Subj: ONR Grant N00014-99-1-0275

Encl: (1) "Final Report, Shallow Water Mid-Frequency Research and FY07 Experiment" dated 5 May 08, with SF 298

Enclosed please find a copy of our report on the Littoral Environmental Acoustics Research (LEAR) field experiment, part of the Shallow Water 2006 (SW06) project. This document constitutes the Final Technical Report for the subject grant.

Dajun Tang

cc: Administrative Grants Officer, ONR Regional Office Seattle (Sandy Thomson)
Naval Research Laboratory (Code 5227)
Defense Technical Information Center

FINAL REPORT

Shallow Water Mid-Frequency Research and FY07 Experiment

Dajun (DJ) Tang
Applied Physics Laboratory, University of Washington
1013 NE 40th Street, Seattle, WA 98105-6698

phone: (206) 543-1290 fax: (206) 543-6785 email: djtang@apl.washington.edu

Award Number: N00014-99-1-0275
http://www.apl.washington.edu/projects/SW06/

LONG-TERM GOALS

To understand mid-frequency (1-10 kHz) acoustics in shallow waters through measurements and modeling, including propagation, reflection, and forward- and backscatter. The top-level goals of this effort are to understand the important environmental processes, which impact mid-frequency sonar performances in shallow water environments; and to develop means to efficiently collect those environmental data.

OBJECTIVES

The LEAR (Littoral Environmental Acoustics Research) acoustics field experiment, part of Shallow Water 2006 (SW06) project, yielded abundant data sets carefully collected for the purpose of investigating mid-frequency (1-10 kHz) acoustics interacting with environments. Both acoustic data and relevant environmental data were measured contemporaneously to facilitate close model/data comparison.

Acoustics objectives and tasks:

1. Direct-path bottom backscatter – what are the most important physical mechanisms? Equipment: APL 32-element vertical line array and the parametric system of Defence Research and Development Canada (DRDC).
2. Single interface forward scatter – what are the most important physical mechanisms (with Peter Dahl, APL-UW). Equipment: APL's MORAY/BASS (Peter Dahl's Moored Receiving Array/ Broadband Acoustic Source System, a source and receiver set used in combination during the experiment).
3. Short range (500 – 1000 m) propagation through internal waves – can acoustic interaction with internal waves be modeled using deterministic measurements of internal waves? Equipment: APL's MORAY/BASS. In collaboration with oceanographic measurements by Frank Henyey of APL and James Moum of Oregon State University.
4. Long-range (10 km) propagation – can multiple interactions with rough boundaries actually simplify the field present at long ranges? Equipment: APL's MORAY/BASS. Complementary data from Scripps, University of Victoria, and DRDC.

Environmental measurements:
Environmental measurements included *in situ* and remote sensing components. It is important to cover all relevant environments with adequate sampling. The environments include the sea surface (buoys, Hans Graber of University of Miami and Peter Dahl of APL), the water column (internal waves by Henyey and Moum, as well as moorings from Woods Hole Oceanographic Institution), and the sea bottom (APL IMP/Laser, SAMS and the Naval Research Laboratory's chirp sonar and geo-probes, both deployed by NRL's Altan Turgut). The SAMS (Sediment Acoustic-speed Measurement System) is a new APL instrument funded by ONR under DURIP to measure *in situ* sediment sound speed to as deep as 3 m.

APPROACH

We successfully completed the comprehensive LEAR field measurements off the New Jersey coast in the summer of 2006. Starting with assumptions and hypotheses based on current knowledge of the field, we combined acoustics measurements with modeling efforts using the measured environmental parameters to achieve quantitative model/data comparisons of sound fields interacting with bottom, surface and the water column. We started from a local area on the order of 100 m by 100 m, and studied single interactions of sound with the bottom and the surface over space and time. We investigated multiple (2-3 bounces) interactions of sound field with the bottom and surface. The point here is to combine the modeling results dealing with individual interaction into an integrated model. Finally, we started modeling the long- range propagation measurements over a range of 10 km. By necessity, the experiment consisted of an acoustics part and an environmental measurement part. We emphasized carrying out environmental measurements at sufficient resolution to properly answer the acoustic questions to be addressed. The acoustics topics included:

1. Single boundary interaction backscattering – what are the most important physical mechanisms?
2. Single boundary interaction forward reflection and forward scattering – what are the most important physical mechanisms?
3. Multiple boundary interactions – Can we successfully combine our knowledge of single interactions to predict the results of a small number of surface and bottom interactions?
4. Long-range (10–20 km) propagation and reverberation – can multiple interactions with boundaries actually simplify the field present at long ranges?

Environmental measurement topics included *in situ* and remote sensing components. They are:

1. In-sediment measurements of sound speed in the bottom, within a layer 1.7 m deep, with spatial resolution of 5-10 cm in depth (Equipment: APL SAMS).
2. *In situ* measurements of bottom roughness and volume heterogeneity over several meters with horizontal spatial resolution of 1 cm and vertical resolution of 1 mm (IMP2 with laser scanner).
3. *In situ* measurements of sea surface roughness spectra and wind speed (Graber, Dahl).
4. Measurement of nonlinear littoral internal waves using a CTD chain vs. time and space (Henyey) and using a multi-purpose probe (Moum).

5. Remote sensing using chirp sonar to estimate sediment geo-acoustic properties over large areas. (Turgut).

In addition, we investigated how to estimate key environmental parameters using only acoustic fields from reflection and backscatter. This will be accomplished by optimizing forward model parameters with acoustic data. For this to be successful, ground truth data (SAMS) in at least one spot is critically necessary.

WORK COMPLETED

We concentrated in the past year on data analysis and modeling. Highlights are:

1. Analysis of SAMS *in situ* measurements of sound speed in three locations within the SW06 area.
2. Analysis of sound scattering by internal solitary waves.
3. Model/data comparison of long range propagation of mid-frequency sound in shallow water.
4. Analysis of seafloor roughness from conductivity and laser scan measurements to support bottom backscatter modeling.

RESULTS

1. The SAMS analysis shows that the top 1.7 m sediments are homogeneous with a mean sound speed of 1610 m/s. This result will be important to the SW06 community to support various inversion schemes. Two papers on this subject are being prepared for the JASA-EL special issue. A new ONR post-doctorate scholar, Jie Yang, has been heavily involved in the data analysis.
2. The work on mid-frequency sound interaction with internal waves has been done through two collaborations, one with Henyey, the other with Moum. This part of research is unique in that we measured deterministic features of the internal waves in the acoustic path. These kinds of measurements make it possible to make non-stochastic model/data comparison. Observed are effects of splitting of arrivals due to the presence of solitary waves and due to the change of thermocline depth before and after the internal waves. Two papers on this subject are being prepared for the JASA-EL special issue.
3. Long range propagation measurements during SW06 were made by several institutions along the same acoustic path. We concentrated on mid-frequency sound propagation in the range of 1 km to 10 km. It was found that sound waves in the shallow water environment behave like deep water waves when the range exceeds 4 km, due to the trapping of waves in the sound channel between the surface thermocline and a warm bottom layer from a front. One paper on this subject is being prepared for the JASA-EL special issue.
4. A new laser scanner was developed, in collaboration with Wang of Taiwan, and deployed along with IMP2, an APL sediment conductivity system, to measure bottom roughness. Two major accomplishments were achieved in this effort. The first is that the laser scanner was able to measure bottom roughness to mm scales, making it possible to support modeling bottom backscatter to much higher frequencies than before. The overlapping regions of the laser scanner and IMP2

yielded consistent results. The second is that we were able to estimate shell distributions on the seafloor – paving the way to quantitatively assess scattering by shell fragments.

IMPACT/APPLICATIONS

While the LEAR experiment addresses many basic science questions, our goal is to improve mid-frequency sonar performance in shallow waters environments. We anticipate impacts in three areas: First, because we measured all relevant environmental parameters influencing sound waves, we will be able to identify the important environmental processes, hence being able to show the applied community what environmental processes to focus on. Second, the direct measurement of sound speed in sediment using SAMS provided a basis for validating bottom inversion schemes. Third, the study on sound interaction with internal waves could provide insight into reverberation clutter. Finally, the laser scanner results provide unprecedented details of bottom scatterers which are sources of backscatter and reverberation.

RELATED PROJECTS

NonLinear Internal Wave Initiative (NLIWI).

PUBLICATIONS

Tang, D., F. S. Henyey, Z. Wang, K. L. Williams, D. Rouseff, P. H. Dahl, J. Quijano, and Jee Woong Choi, "Mid-frequency acoustic propagation in shallow water on the New Jersey shelf I: Mean intensity", *J. Acoust. Soc. Am.* (submitted).

Tang, D., F. S. Henyey, Z. Wang, K. L. Williams, D. Rouseff, P. H. Dahl , J. Quijano, and Jee Woong Choi, "Mid-frequency acoustic propagation in shallow water on the New Jersey shelf II: Fluctuations", *J. Acoust. Soc. Am.* (submitted).

Henyey, F.S., K. L. Williams, and D. Tang, "Simultaneous nearby measurements of acoustic propagation and high-resolution sound speed structure containing internal waves," *J. Acoust. Soc. Am.* (submitted).

Rouseff, D., D. Tang, K. L. Williams, J. Moum, F. S. Henyey, and Z. Wang, "Mid-frequency sound propagation through internal waves at short range with synoptic oceanographic observations," *J. Acoust. Soc. Am.* (submitted).

Tang, D., K. L. Williams, J. Yang, R. Light, and V.Miller, "A sediment acoustics measurement system (SAMS) to acquire *in situ* sound speed, *J. Acoust. Soc. Am.* (submitted).

Yang, J., D. Tang, and K. L.Williams, "Direct Measurements of Sediment Sound Speed Using SAMS in SW06," *J. Acoust. Soc. Am.* (submitted).

Wang, C., and D. Tang, “Seafloor roughness measured by a laser line scanner and a conductivity probe,” *J. Acoust. Soc. Am.* (submitted).

Wang, C., and D. Tang, “Seafloor Shell Fragments Characterization for Acoustic Applications”, *J. Acoust. Soc. Am.* (submitted).

Tang, D., K. L. Williams, and E. I. Thorsos, “Remote sensing of sand ripples using high-frequency backscatter,” *J. Acoust. Soc. Am.* (2008 accepted).

Leifer, I. and D. Tang, “The acoustic signature of marine seep bubbles,” *J. Acoust. Soc. Am.*, 121 EL35-EL40 (2006)

Rouseff, D. and D. Tang, “Internal wave effect on the ambient noise notch in the East China Sea,” *J. Acoust. Soc. Am.*, 120 1284-1294 (2006)

Tang, D. “Fine-scale measurements of sediment roughness and subbottom variability,” *IEEE J. Oceanic Engineering*, Vol. 29, 929-939, October (2004).

Miller, J. H., L. R. Bartek, G. R. Potty, D. Tang, J. Na, and Y. Qi, “Sediments in the East China Sea,” *IEEE J. Oceanic Engineering*, Vol. 29, 940-951, October (2004).

Tang, D., K. B. Briggs, K. L. Williams, D. R. Jackson, E. I. Thorsos, “Fine-scale volume heterogeneity measurements in sand,” *IEEE J. Oceanic Engineering.*, Vol. 27, 546-560 (2002).

Briggs, K.B., D. Tang, and K. L. Williams, “Characterization of interface roughness of rippled sand off Fort Walton Beach, Florida,” *IEEE J. Oceanic Engineering*, Vol. 27, 505-514 (2002).

Williams, K.L., D. R. Jackson, E. I. Thorsos, D. Tang and K. B. Briggs, “Acoustic backscattering experiments in a well characterized sand sediment: Data/model comparisons using sediment fluid and Biot models,” *IEEE J. Oceanic Engineering*, Vol. 27, 376-387 (2002).

Williams, K.L., D. R. Jackson, E. I. Thorsos, and D. Tang, “Comparison of sound speed and attenuation measured in a sandy sediment to predictions based on the Biot theory of porous media,” *IEEE J. Oceanic Engineering, Vol.* 27, 413-428 (2002).

Chu, D., D. Tang, T.C. Austin, A.A. Hinton, and R.I. Arthur, “Fine-scale acoustic tomographic imaging of shallow water sediments,” *IEEE Journal of Oceanic Engineering, Vol.* 26, 70-81 (2001).

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
05-05-2008	final technical	01 JAN 99 - 31 DEC 07

4. TITLE AND SUBTITLE
Final Report: Shallow Water Mid-Frequency Research and FY07 Experiment

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-99-1-0275

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Tang, Dajun

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Applied Physics Laboratory, University of Washington
1013 NE 40th St.
Seattle, WA 98105-6698

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
875 N. Randolph St.
One Liberty Center
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The LEAR (Littoral Environmental Acoustics Research) acoustics field experiment, part of Shallow Water 2006 project, collected abundant data sets in 2006 to investigate mid-frequency acoustics interacting with environments. Starting with hypotheses based on current knowledge, we combined acoustics measurements with modeling using measured environmental parameters to achieve quantitative model/data comparisons. The impact of this work will be in three areas: First, because we measured all relevant environmental parameters we will be able to identify important environmental processes and show what environmental processes to focus on. Second, direct measurement of sound speed in sediment using SAMS provided a basis for validating bottom inversion schemes. Third, study of sound interaction with internal waves could provide insight into reverberation clutter. Finally, the laser scanner results provide unprecedented details of bottom scatterers which are sources of backscatter and reverberation.

15. SUBJECT TERMS
shallow water, backscatter, forward scatter, internal waves, bottom roughness

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	5	Ellen S. Livingston

19b. TELEPONE NUMBER (*Include area code*)
703-696-4203